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KNOCK-LIMITED PERFORMANCE OF PURE HYDROCARBONS BLENDED WITH A BASE FUEL IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER

II - TWELVE AROMATICS

By Arthur W. Bull and Anthony W. Jones

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WASHINGTON

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SUMMARY

An investigation of the knock-limited performance of leaded blends of 12 pure aromatic hydrocarbons was conducted in a full-scale aircraft-engine cylinder at CRC simulated cruise and take-off conditions to determine the antiknock effectiveness of additions of pure compounds to aviation fuels. The following fuels were investigated:

1,3,5-Trimethylbenzene (mesitylene)
m-Diethylbenzene
p-Xylene
1-Ethyl-4-methylbenzene
tert-Butylbenzene
Isopropylbenzene (cumene)
Toluene
Ethylbenzene
sec-Butylbenzene
Benzene
1,2,4-Trimethylbenzene (pseudocumene)
o-Xylene

Each of these aromatic fuels was blended with a base fuel (85 percent S-3 and 15 percent M-4 plus 4 ml TEL/gal) and the final blend was leaded to 4 ml TEL per gallon. The base fuel and the S-3 reference-fuel blends were also tested separately. Curves of S-3 reference fuels having lead concentrations below 3.0 ml TEL per gallon were obtained to partly bracket the test-fuel curves.

The results of the investigation indicated that:

1. The 12 pure aromatic hydrocarbons increased the knock limit of the base fuel at the simulated cruise conditions with the exception of 1,2,4-trimethylbenzene and o-xylene in the fuel-air-ratio range of 0.057 to 0.090.

2. The 12 pure aromatic hydrocarbons increased the knock limit of the base fuel at the take-off conditions with the exception of benzene, 1,2,4-trimethylbenzene, and o-xylene in the fuel-air-ratio range of 0.054 to 0.080.

INTRODUCTION

A general investigation to determine the antiknock effectiveness of additions of pure hydrocarbons to aircraft-engine fuels is being conducted by the NACA. The program includes tests with a 17.6 engine, an F-3 engine, an F-4 engine, and a full-scale aircraft-engine cylinder. Tests of the knock-limited performance of eight pure paraffins and two pure olefins blended and leaded with a base fuel in a full-scale aircraft-engine cylinder are reported in reference 1. Ratings of the fuel blends by F-3 and F-4 methods are also given.

The present report gives the results of knock tests with leaded blends of 12 pure aromatic hydrocarbons and a base fuel at cruise and take-off conditions according to the same procedure used in tests of paraffinic and olefinic fuel blends reported in reference 1. The aromatic hydrocarbons were synthesized or purchased and then purified at the Aircraft Engine Research Laboratory of the NACA at Cleveland, Ohio. Tests were run between January and March 1944 in a full-scale aircraft-engine cylinder under conditions recommended by the Coordinating Research Council. A summary of this report is given in reference 2; the present report presents the complete data including F-3 and F-4 ratings for all 12 aromatic fuel blends.

FUELS

The Organic Synthesis Section of AERL prepared for the full-scale single-cylinder tests 5 gallons each of the following pure aromatic hydrocarbons leaded to a concentration of 4.0 ml TEL per gallon:

1,3,5-Trimethylbenzene (mesitylene)
m-Diethylbenzene
p-Xylene
1-Ethyl-4-methylbenzene
tert-Butylbenzene
Isopropylbenzene (cumene)
Toluene

Ethylbenzene
sec-Butylbenzene
Benzene
1,2,4-Trimethylbenzene (pseudocumene)
o-Xylene

The leaded aromatic hydrocarbons were mixed with a base fuel to form blends consisting of 25 percent by volume pure hydrocarbon and 75 percent by volume base fuel as in reference 1. A similar blend was made with the leaded S-3 reference fuel and the base fuel. The base fuel was a blend of 85 percent S-3 and 15 percent M-4 reference fuels leaded to a concentration of 4.0 ml TEL per gallon and was inhibited with 0.09 pound of inhibitor per 500 gallons of fuel.

The reference fuels used to partly bracket the test fuels were:

Blend of 90 percent S-3 plus 10 percent M-4
S-3
S-3 plus 0.5 ml TEL per gallon
S-3 plus 1.25 ml TEL per gallon
S-3 plus 2.0 ml TEL per gallon
S-3 plus 3.0 ml TEL per gallon

APPARATUS AND METHODS

Apparatus. - The tests were conducted on a R-1820 G200 cylinder mounted on a CUE crankcase. The auxiliary apparatus used in these tests was the same as that used in reference 1 except that a heat exchanger was installed in the cooling-air line to control the cooling-air temperature.

Test conditions. - The fixed engine conditions were:

	CRC simulated cruise	CRC simulated take-off
Compression ratio	7.3	7.3
Spark advance, deg B.T.C. (both plugs)	20	20
Engine speed, rpm	2000	2500
Inlet-air temperature, °F	210	250
Oil flow to piston jets, pounds per minute	8	8
Oil-in temperature, °F	180 to 190	180 to 190
Gasoline temperature at entrance to injection pump, °F	60 to 80	60 to 80

	CRC simulated cruise	CRC simulated take-off
Cooling-air temperature, °F	85±2	85±2
Valve timing:		
Intake opens, deg B.T.C.	15	15
Intake closes, deg A.B.C.	44	44
Exhaust opens, deg B.B.C.	74	74
Exhaust closes, deg A.T.C.	25	25

The cooling-air flow was determined for each test by running the engine at a brake mean effective pressure of 140 pounds per square inch and a fuel-air ratio of 0.10 and by adjusting the damper valve in the cooling-air line until the temperature of the rear spark-plug bushing was 365° F. The cooling-air flow thus determined was maintained constant for each test.

Knock was detected with a magnetostriction pickup unit, which was inserted into the combustion chamber and used in conjunction with a cathode-ray oscillograph.

Test procedure. - Because the supply of pure aromatic fuel blends was limited, special procedures were used for obtaining complete mixture-response curves as rapidly as possible at both cruise and take-off conditions. These special procedures are described in detail in reference 1.

The valve clearances, the gaps between the spark-plug electrodes and the magnetos were checked at least once a day and a run of three or four knock points was made with the base fuel before each test-fuel run to check engine conditions.

Mixture-response curves for the reference fuels were determined at take-off and cruise conditions to partly bracket the test fuels. Friction runs were made after each test.

The F-3 and F-4 ratings for the 25-percent blends were also determined for the 12 pure aromatic hydrocarbons.

Precision of tests. - The variation of the knock-limited indicated mean effective pressure of the base fuel during the tests is shown in figure 1. The average curve for the base fuel was faired and the symbols on the figure indicate the reproducibility of the base-fuel check runs made before each test-fuel run. The variation in engine behavior was greater than that found in reference 1 and was probably caused by the higher powers and higher temperatures experienced with the aromatic fuel blends.

Because some variation was experienced in checking the base fuel at cruise conditions, an average curve was plotted. At take-off conditions the variation was negligible.

RESULTS AND DISCUSSION

The reference-fuel framework covering tests at both operating conditions is presented in figures 2 and 3. From these figures cross plots were made (fig. 4) to facilitate conversion of the knock-limited indicated mean effective pressures of the test fuels to lead ratings. Conversion of the knock limits of test fuels to percentage S reference fuel in M reference fuel was made from the curves in figure 5; the curves were cross-plotted from the data in figures 2 and 3 by using equation (3b) of reference 3, which gives a relation of the reciprocal indicated mean effective pressure. No mixture-response curves for reference fuels with lead concentrations above 3.0 ml TEL per gallon are presented because mechanical difficulties encountered during tests with higher lead concentrations necessitated a complete engine overhaul.

Figures 6 and 7 compare the performance of a blend of 25 percent by volume S-3 reference fuel in the base fuel with the performance of the base fuel.

The knock-limited performance of the blends of the 12 pure aromatic hydrocarbons and the base fuel is presented in figures 8 and 9 and in table I. All of the aromatics tested with the exception of o-xylene increased the knock-limited power of the base fuel in the rich region; 1,3,5-trimethylbenzene, m-diethylbenzene, p-xylene, and 1-ethyl-4-methylbenzene caused the greatest increases at a fuel-air ratio of 0.10 at both operating conditions. In the lean region (fuel-air ratio of 0.065) all of the aromatic hydrocarbons except o-xylene and 1,2,4-trimethylbenzene at 2000 rpm and o-xylene, 1,2,4-trimethylbenzene, and benzene at 2500 rpm increased the knock-limited performance. The greatest increase in the lean region at both operating conditions was obtained with m-diethylbenzene. The lean-region performance of the aromatics with the exception of o-xylene and 1,2,4-trimethylbenzene decreased as the severity of operating conditions increased.

The correlation of the performance of the fuels in a full-scale aircraft-engine cylinder with that in an F-4 engine is given in figures 10 and 11 on the basis of the ratio of indicated mean effective pressure of the test fuel to indicated mean effective pressure of the base fuel because no reference-fuel curves could be

obtained to bracket all the test fuels. The correlation is poor at fuel-air ratios of either 0.07 or 0.10 but shows a better trend at 0.10 fuel-air ratio. The increase in knock-limited power with the aromatic blends at 0.10 fuel-air ratio was greater in the full-scale aircraft-engine cylinder at both operating conditions than in the F-4 engine, indicating that the F-4 tests were more severe than the full-scale-cylinder tests. At both engine speeds and a fuel-air ratio of 0.10, the average increase in power resulting from the addition of aromatics was 70 percent more with the full-scale single cylinder than the average increase observed with the F-4 engine.

The correlation between the F-3 ratings and the full-scale-cylinder ratings at a fuel-air ratio of 0.070 is given in figure 12. At 2000 rpm all of the fuels except the o-xylene blend gave higher ratings in the full-scale cylinder than in the F-3 engine. At 2500 rpm o-xylene and benzene blends had lower ratings in the full-scale cylinder than in the F-3 engine, but the high-performance fuels showed considerably higher ratings in the full-scale cylinder than in the F-3 engine. The range covered by the F-3 ratings was from 100 to 121 performance number, whereas the range of ratings covered by the full-scale single cylinder at 2500 rpm and 0.070 fuel-air ratio was from 78 to 136 performance number. The F-3 engine overrates the low-performance aromatics and underrates the high-performance aromatics.

SUMMARY OF RESULTS

Results of knock tests on a R-1820 G200 cylinder run at cruise conditions, engine speed of 2000 rpm and an inlet-air temperature of 210° F, and at take-off conditions, engine speed of 2500 rpm and an inlet-air temperature of 250° F, are given in table I. These data show that:

1. All of the 12 pure aromatic hydrocarbons increased the knock limit of the base fuel at the 2000 rpm conditions except 1,2,4-trimethylbenzene and o-xylene, both of which lowered the knock limit at a fuel-air ratio of approximately 0.065.

2. All of the 12 pure aromatic hydrocarbons increased the knock limit of the base fuel at the 2500 rpm conditions except benzene, 1,2,4-trimethylbenzene, and o-xylene. Benzene and 1,2,4-trimethylbenzene decreased the knock limit in the lean region (approximately 0.065 fuel-air ratio) but increased the knock limit in the rich region. o-Xylene decreased the knock limit in the lean region and made no change in the rich region.

3. The effectiveness of pure aromatic hydrocarbons as antiknock additives decreased in the lean region as the severity of operating conditions increased.

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REFERENCES

1. Jones, Anthony W., and Bull, Arthur W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. I - Eight Paraffins, Two Olefins. NACA ARR No. E4E25, 1944.

2. Bull, Arthur W., and Jones, Anthony W.: Summary Report on the Knock-Limited Performance of 12 Pure Aromatic Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. NACA ARR No. E4F06, 1944.

3. Sanders, Newell D.: A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. NACA ARR No. 3H21, 1943.

TABLE I. - COMPARISON OF RATINGS OBTAINED IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER WITH F-4 AND F-3 RATINGS

[For each compound there are three rows of values. The first row is imep, lb/sq in.; the second is tetraethyl lead in S reference fuel, ml/gal, except as noted; and the third is ratio of imep of test fuel to imep of base fuel.]

Compound	Concentration in base fuel (percent by volume)	F-3 ratings	F-4 ratings				Full-scale-cylinder ratings (compression ratio, 7.3; spark advance, 20° B.T.C.)									
							Engine speed, 2000 rpm; inlet-air temperature, 210° F					Engine speed, 2500 rpm; inlet-air temperature, 250° F				
			Fuel-air ratio				Fuel-air ratio					Fuel-air ratio				
			Lean	0.07	0.10	Rich	0.065	0.07	0.08	0.09	0.10	0.065	0.07	0.08	0.09	0.10
1,3,5-Trimethylbenzene (mesitylene)	25	-------	94	109	233	270	199	210	258	305	344	184	196	272	332	371
		0.76	0.32	0.37	5.20	>6.00	1.91	2.62	(a)	(a)	(a)	1.25	1.57	(a)	(a)	(a)
		-------	0.98	0.95	1.39	1.59	1.34	1.39	1.50	1.58	1.62	1.19	1.25	1.55	1.68	1.72
m-Diethylbenzene	25	-------	106	147	241	261	248	258	308	338	348	196	222	294	337	350
		0.60	0.29	1.03	4.00	>6.00	(a)	(a)	(a)	(a)	(a)	2.20	(a)	(a)	(a)	(a)
		-------	0.95	1.07	1.42	1.52	1.67	1.71	1.79	1.75	1.63	1.26	1.41	1.67	1.71	1.62
p-Xylene	25	-------	111	146	243	261	132	198	278	324	345	184	190	264	314	354
		0.53	0.35	0.65	4.00	6.00	0.79	1.25	(a)	(a)	(a)	1.25	1.25	(a)	(a)	(a)
		-------	0.99	1.09	1.39	1.49	1.23	1.31	1.62	1.68	1.62	1.19	1.21	1.50	1.59	1.64
1-Ethyl-4-methylbenzene	25	-------	106	136	231	256	227	230	278	327	354	184	185	247	325	351
		0.47	0.41	0.42	3.56	5.80	(a)	(a)	(a)	(a)	(a)	1.25	1.03	(a)	(a)	(a)
		-------	0.98	1.01	1.34	1.47	1.53	1.52	1.62	1.69	1.66	1.19	1.18	1.40	1.65	1.62
tert-Butylbenzene	25	-------	135	162	246	260	220	225	264	306	331	192	204	251	302	331
		0.77	0.98	1.68	4.60	5.72	(a)	(a)	(a)	(a)	(a)	1.81	2.08	(a)	(a)	(a)
		-------	1.11	1.17	1.42	1.48	1.49	1.49	1.54	1.59	1.55	1.24	1.30	1.43	1.53	1.53
Isopropylbenzene (cumene)	25	-------	97	127	209	237	207	206	248	300	316	194	199	235	284	318
		0.53	0.42	0.50	3.07	3.92	2.59	2.37	(a)	(a)	(a)	2.00	1.75	2.63	(a)	(a)
		-------	1.02	1.07	1.23	1.43	1.40	1.36	1.44	1.55	1.48	1.25	1.27	1.34	1.44	1.47
Toluene	25	-------	119	153	227	247	190	196	236	280	317	170	176	238	280	302
		0.34	0.34	0.55	2.90	3.85	1.08	1.11	2.95	(a)	(a)	0.73	0.71	2.92	(a)	(a)
		-------	0.98	1.04	1.29	1.44	1.28	1.30	1.37	1.45	1.49	1.10	1.12	1.35	1.42	1.40
Ethylbenzene	25	-------	127	159	227	244	200	210	248	278	296	174	192	234	269	294
		0.40	0.50	0.90	3.31	4.36	2.00	2.62	(a)	(a)	(a)	0.84	1.36	2.54	(a)	(a)
		-------	1.04	1.08	1.29	1.41	1.35	1.39	1.44	1.44	1.39	1.12	1.22	1.33	1.37	1.36
sec-Butylbenzene	25	-------	110	135	212	229	198	202	231	270	295	180	174	243	275	291
		0.54	0.50	0.50	2.38	2.86	1.80	1.81	2.68	(a)	(a)	1.06	0.66	(a)	(a)	(a)
		-------	1.03	1.01	1.25	1.33	1.34	1.34	1.34	1.40	1.38	1.16	1.11	1.38	1.40	1.35
Benzene	25	-------	84	126	196	210	177	180	201	232	263	150	146	193	229	258
		0.31	0.18	0.90	2.00	1.90	0.67	0.57	0.64	1.25	2.14	0.37	0.20	0.49	1.03	1.50
		-------	0.92	1.10	1.15	1.23	1.20	1.19	1.17	1.20	1.23	0.97	0.93	1.10	1.16	1.19
1,2,4-Trimethylbenzene (pseudocumene)	25	-------	96	117	174	177	110	132	178	206	229	136	136	182	221	238
		[b]98.8	[b]100	0.19	0.41	0.31	[c]99.3	0.05	0.26	0.41	0.60	0.19	0.10	0.33	0.73	0.71
		-------	0.83	0.85	1.03	1.03	0.74	0.87	1.03	1.07	1.08	0.88	0.87	1.03	1.12	1.10
o-Xylene	25	-------	83	105	155	155	114	124	163	193	211	119	111	172	195	213
		[b]100	[c]96.1	0.10	0.15	[c]98.1	0.01	0.01	0.12	0.22	0.20	[c]100	[c]87.0	0.22	0.24	0.19
		-------	0.75	0.80	0.91	0.90	0.77	0.82	0.95	1.00	0.99	0.77	0.71	0.98	0.99	0.99
S-3 reference fuel	25	-------	----	----	----	----	160	165	186	208	228	158	166	195	217	235
		-------	----	----	----	----	0.38	0.33	0.37	0.44	0.57	0.50	0.47	0.53	0.60	0.60
		-------	----	----	----	----	1.08	1.09	1.08	1.08	1.07	1.02	1.06	1.11	1.10	1.09
Base fuel (85% S-3 and 15% M-4 + 4 ml TEL/gal)	100	-------	[d]110	[d]130	[d]170	[d]175	[d]148	[d]151	[d]172	[d]193	[d]213	155	157	176	197	216
		0.39	0.36	0.41	0.31	0.26	0.24	0.18	0.20	0.22	0.24	0.45	0.33	0.27	0.26	0.23
		-------	----	----	----	----	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

[a]Greater than S-3 + 3.0 ml TEL/gal.
[b]Octane number.
[c]Percentage S-3 in M-4 reference fuels.
[d]imep values of base fuel are from average curve made up from a number of base-fuel tests during course of project.

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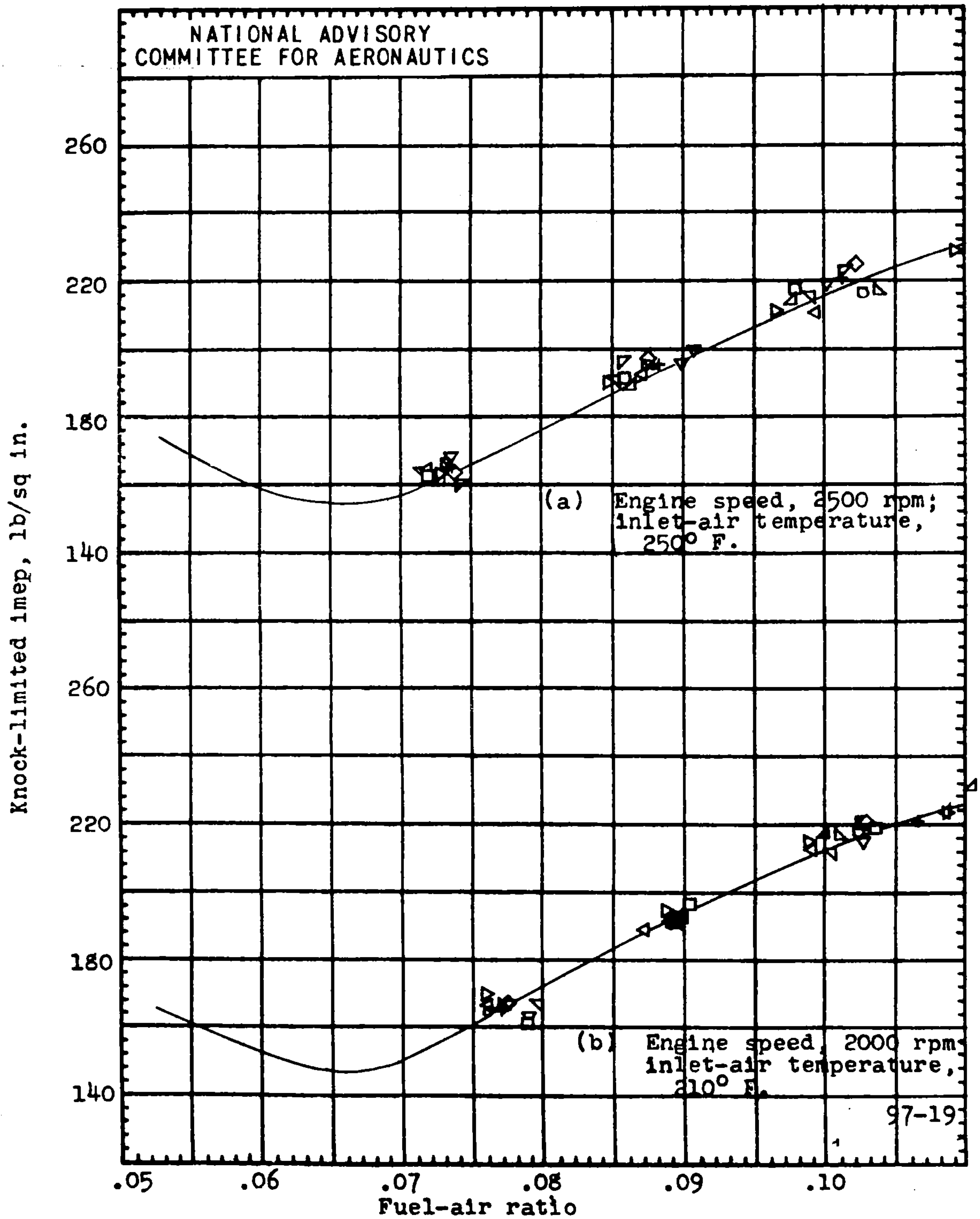


Figure 1. - Reproducibility of knock-limited indicated mean effective pressure with check runs. Fuel, 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon. (Symbols correspond to those in figures 7 and 8 and indicate the base-fuel check points for the test fuels.)

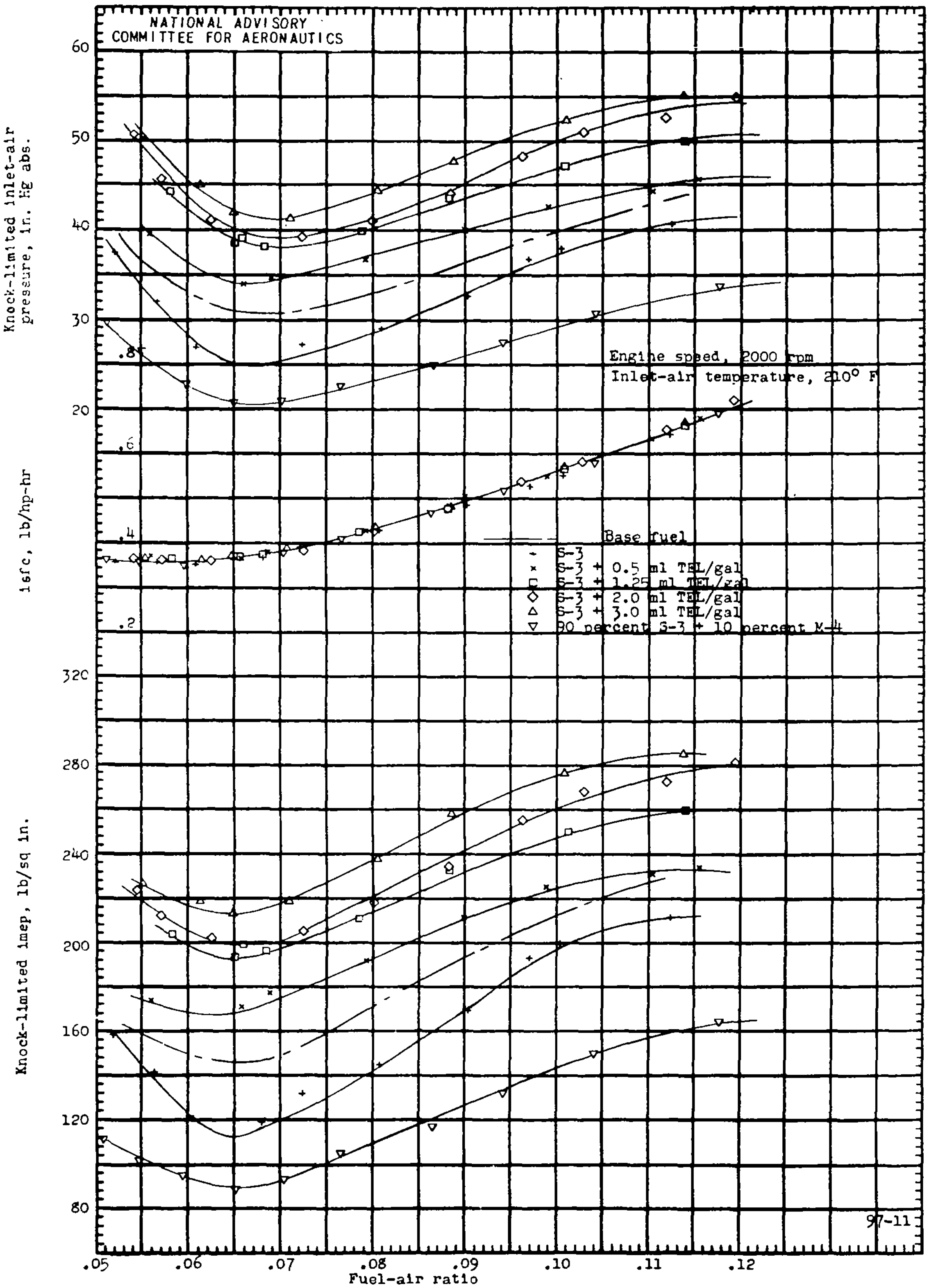


Figure 2. - Reference-fuel framework at an engine speed of 2000 rpm and an inlet-air temperature of 210° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

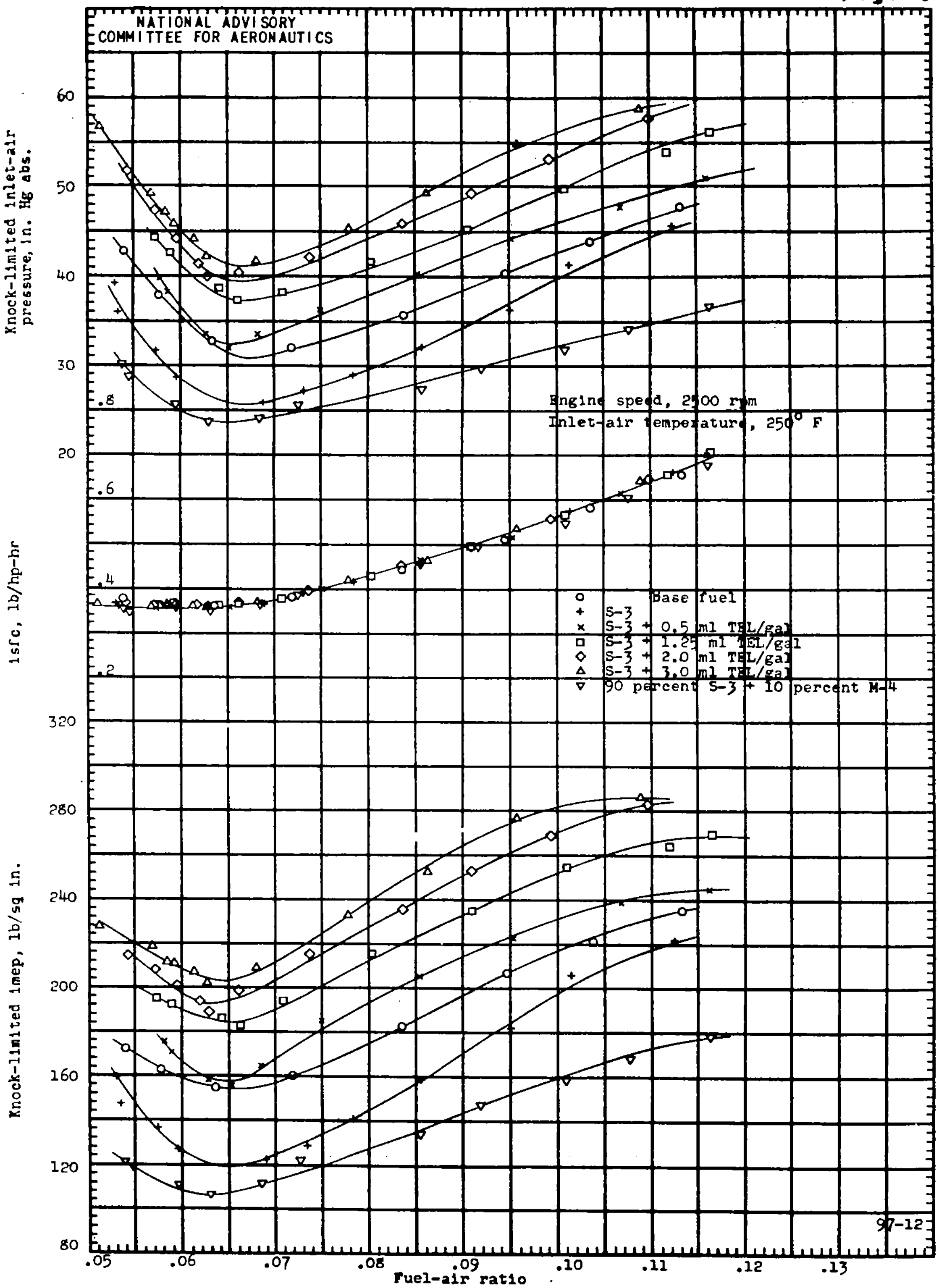


Figure 3. - Reference-fuel framework at an engine speed of 2500 rpm and an inlet-air temperature of 250° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

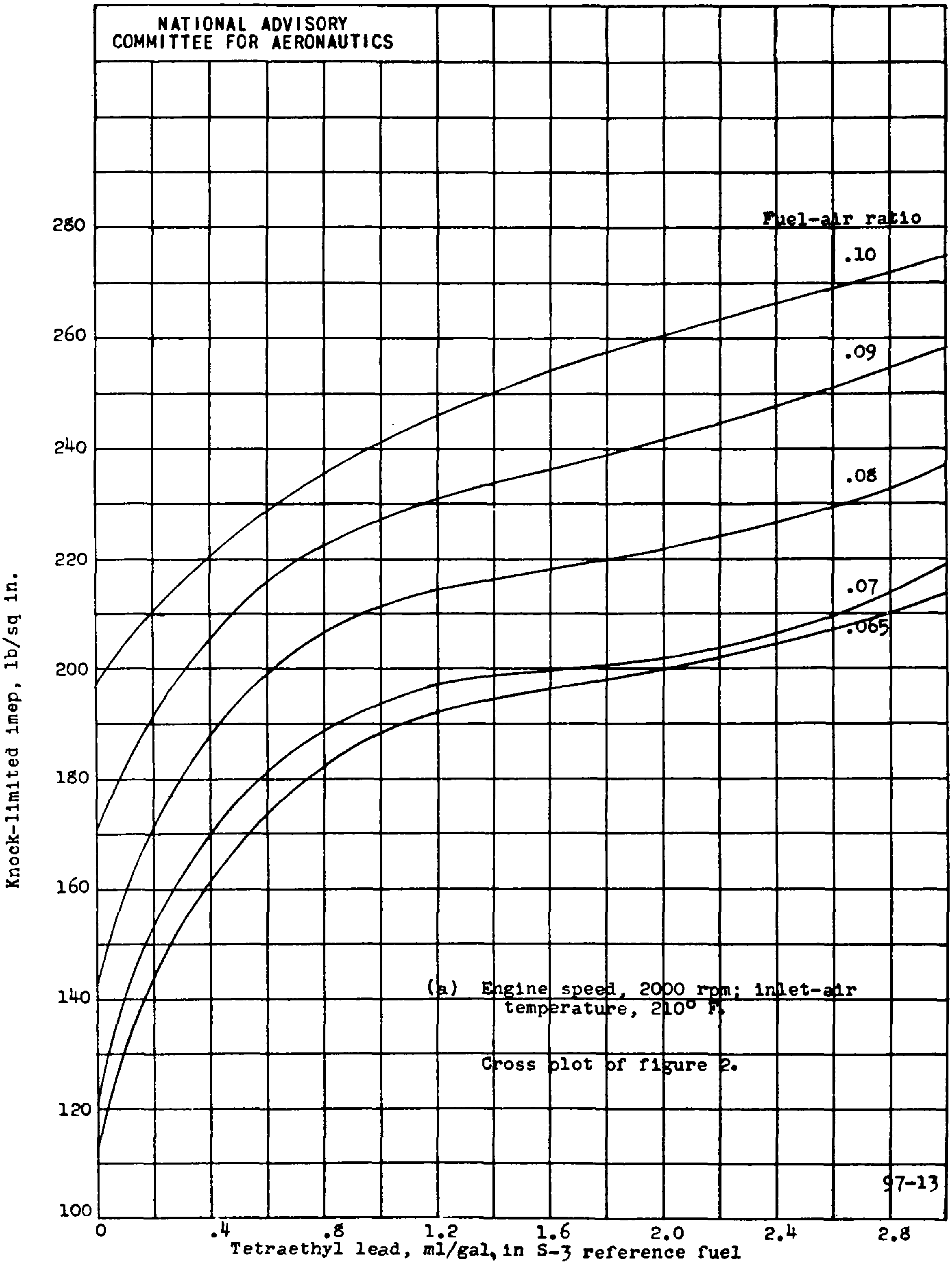


Figure 4. - Relation between knock-limited indicated mean effective pressure and lead concentration in S-3 reference fuel for different fuel-air ratios. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.

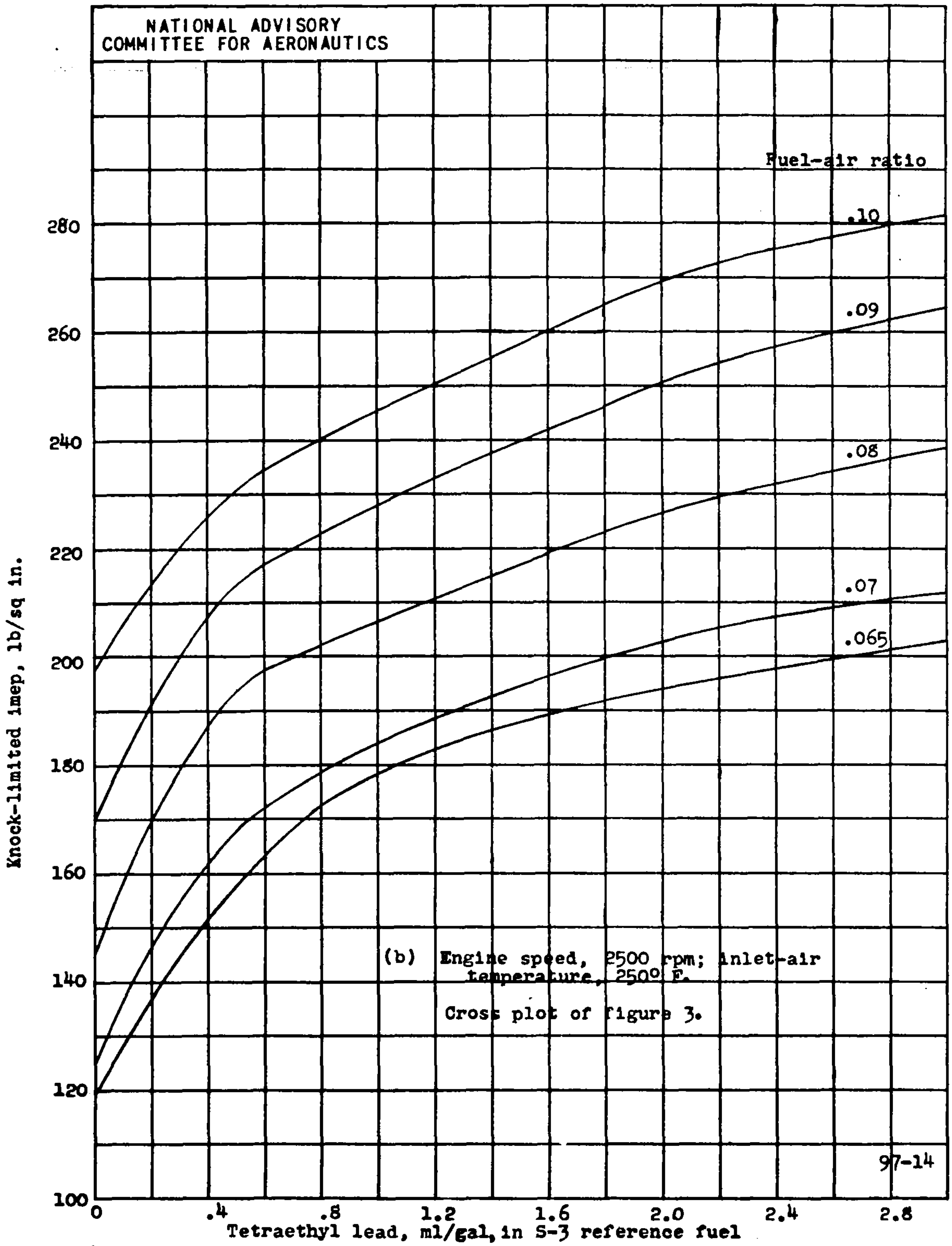


Figure 4. - Concluded.

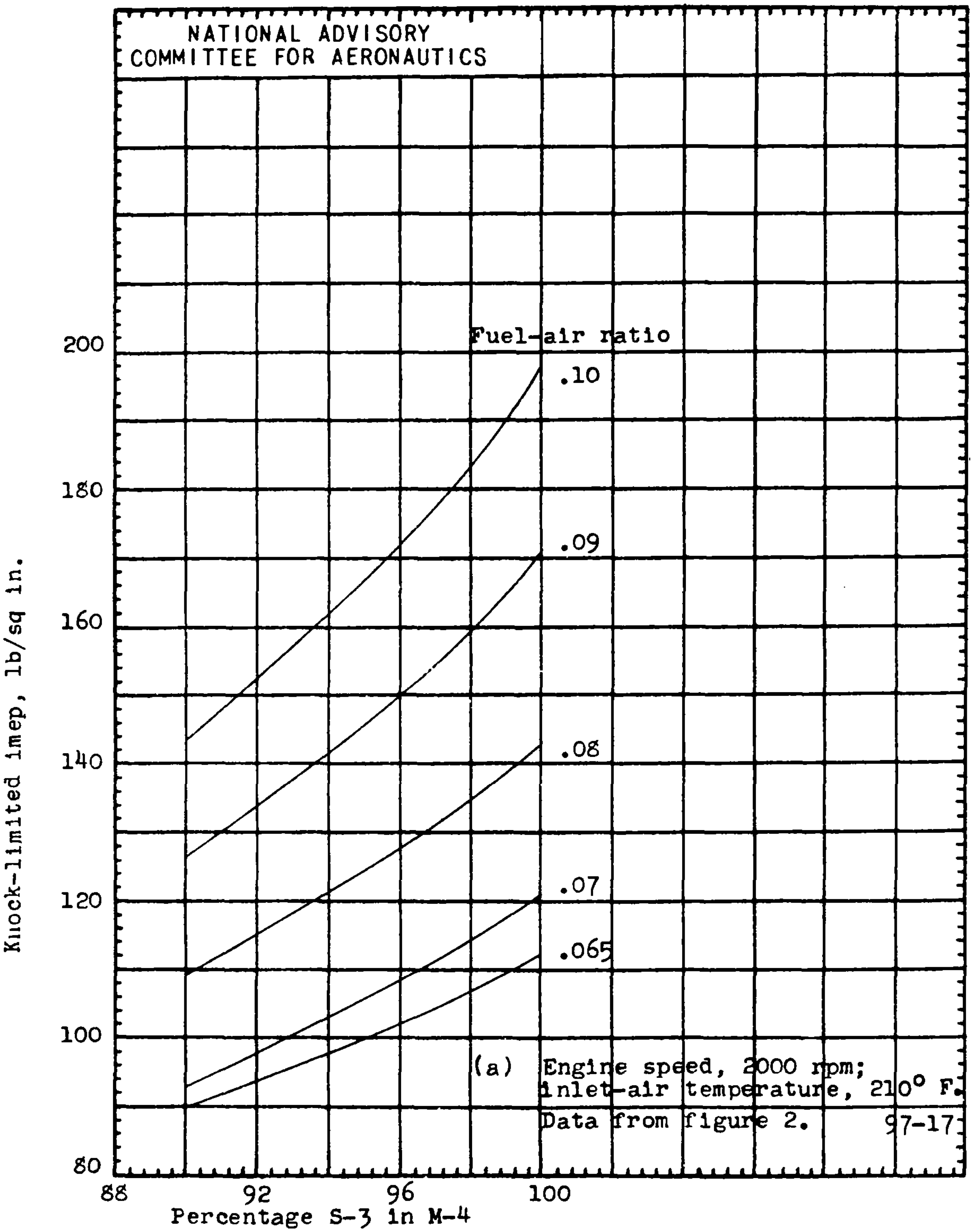


Figure 5. - Relation between knock-limited indicated mean effective pressure and percentage S-3 in M-4 for different fuel-air ratios. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C. Curves plotted by using equation 3(b) of reference 4.

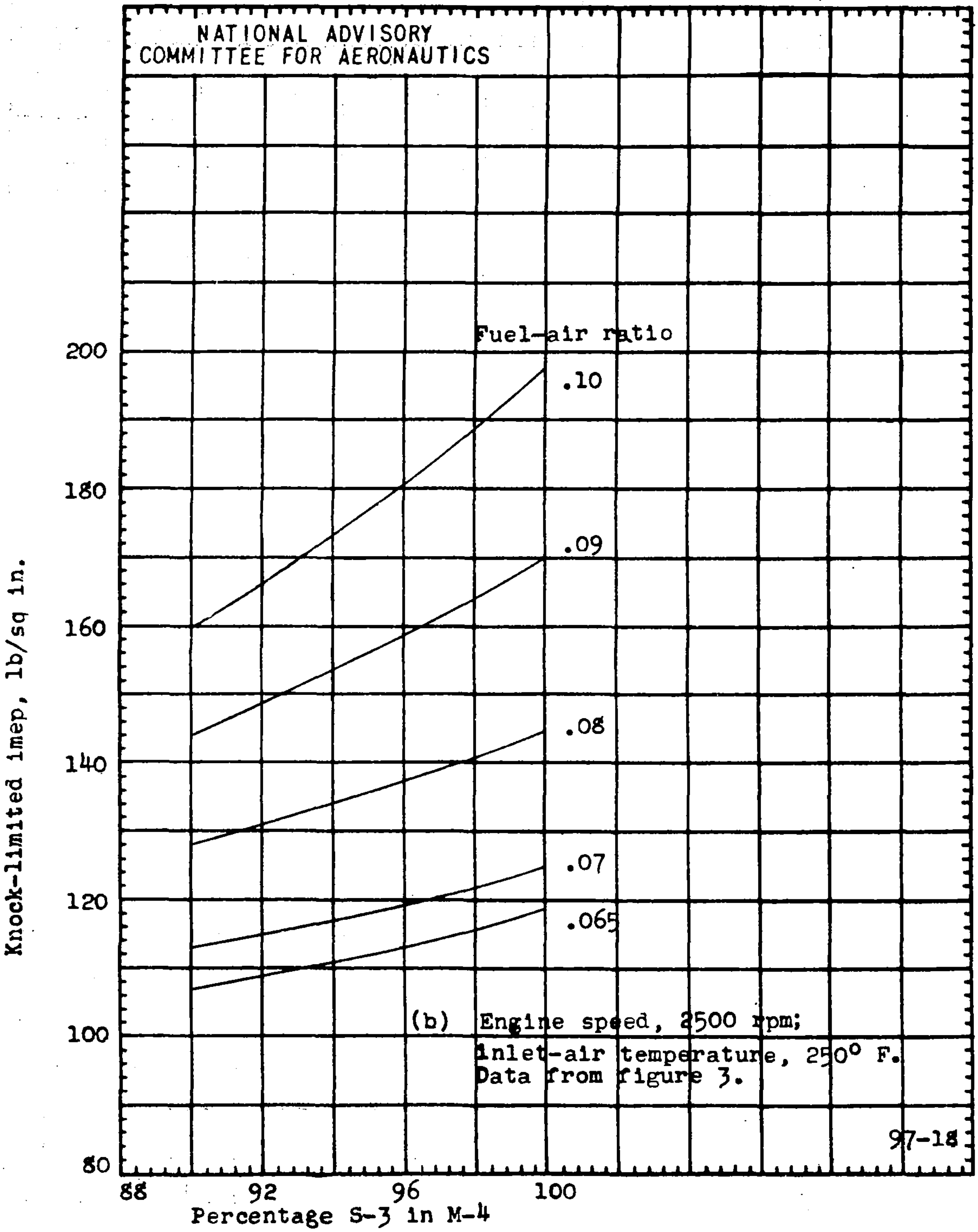


Figure 5. - Concluded.

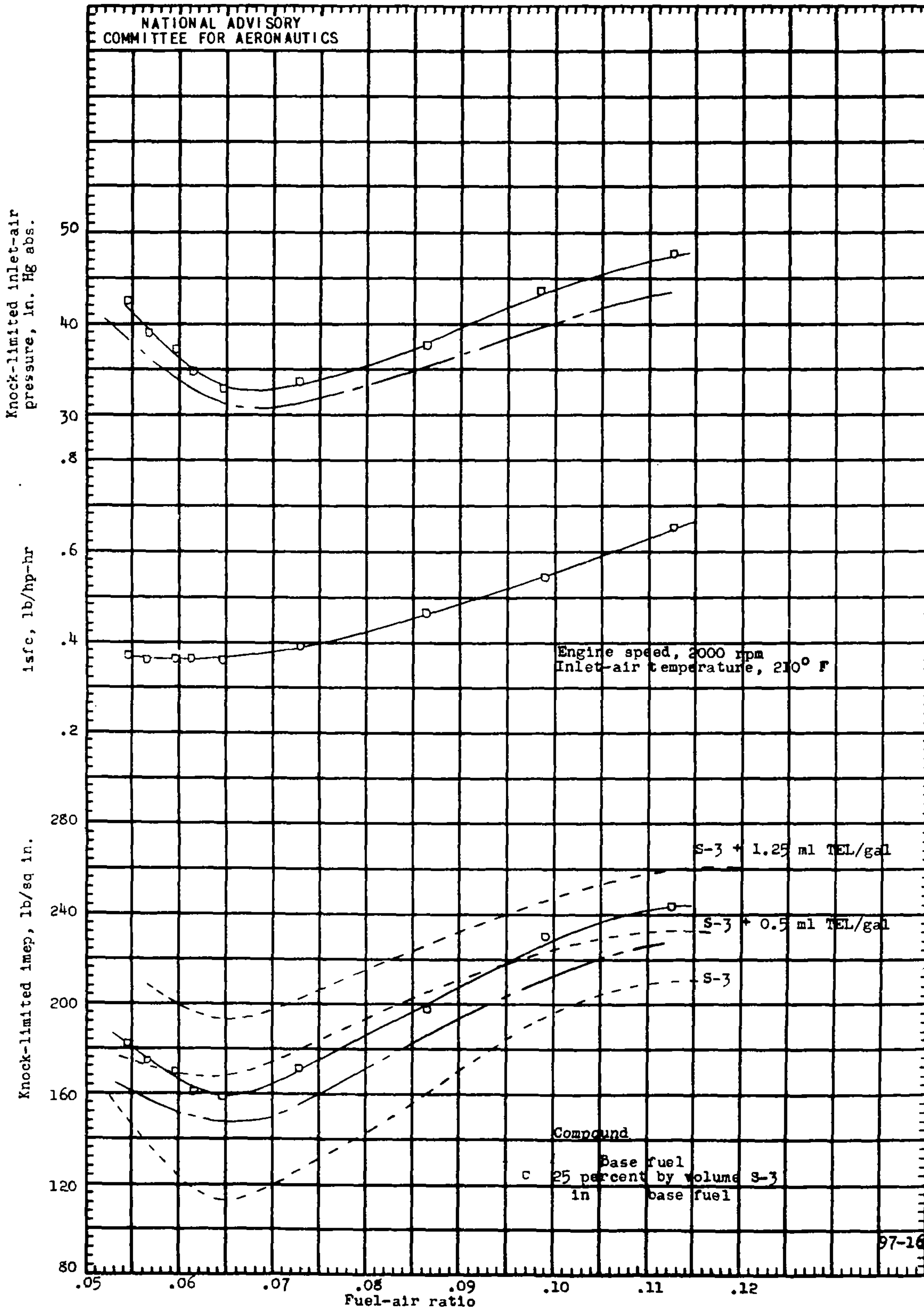


Figure 6. - Knock-limited engine performance of an S-3 blend at an engine speed of 2000 rpm and an inlet-air temperature of 210° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

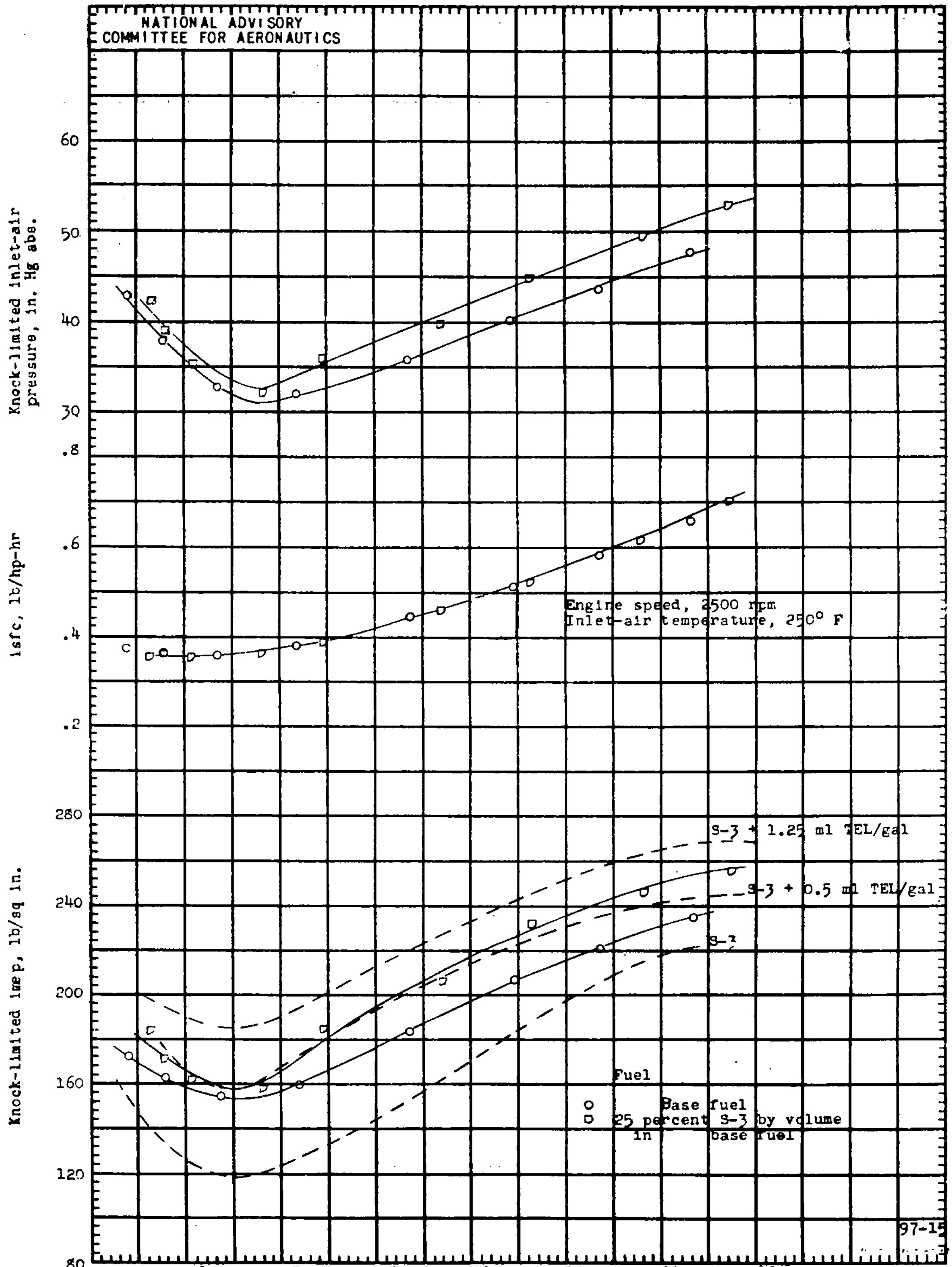
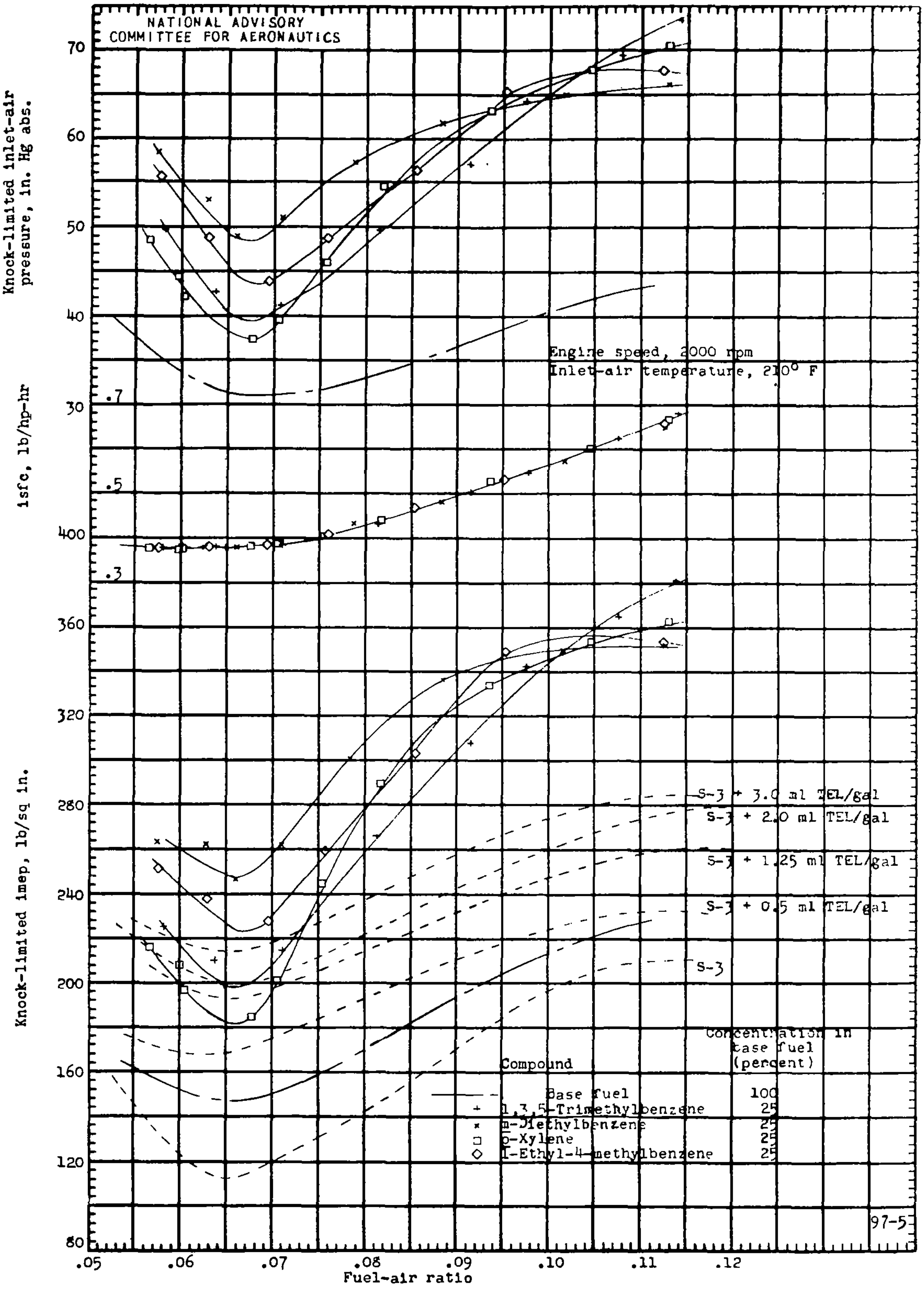
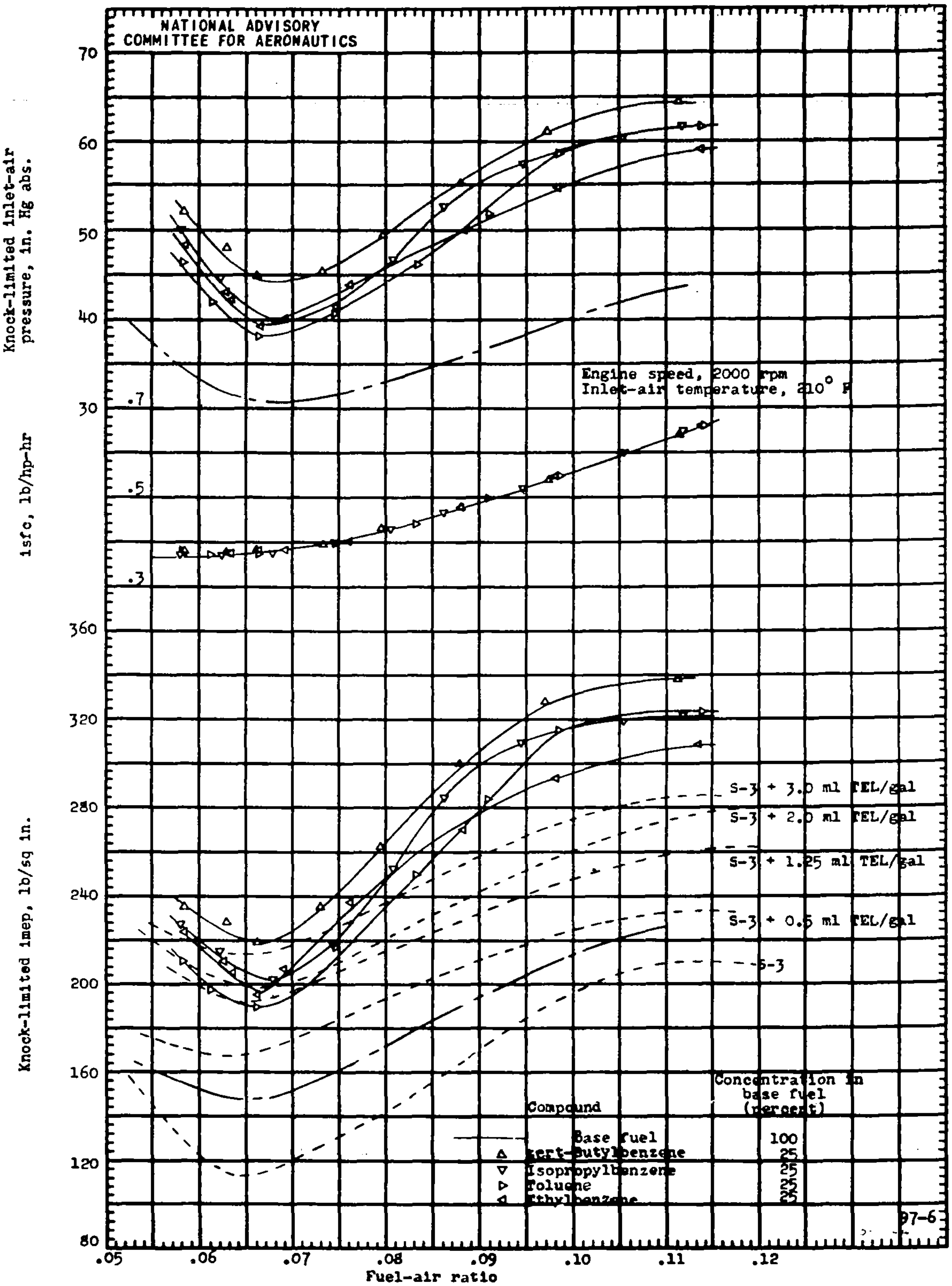


Figure 7. - Knock-limited engine performance of an S-3 blend at an engine speed of 2500 rpm and an inlet-air temperature of 250° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

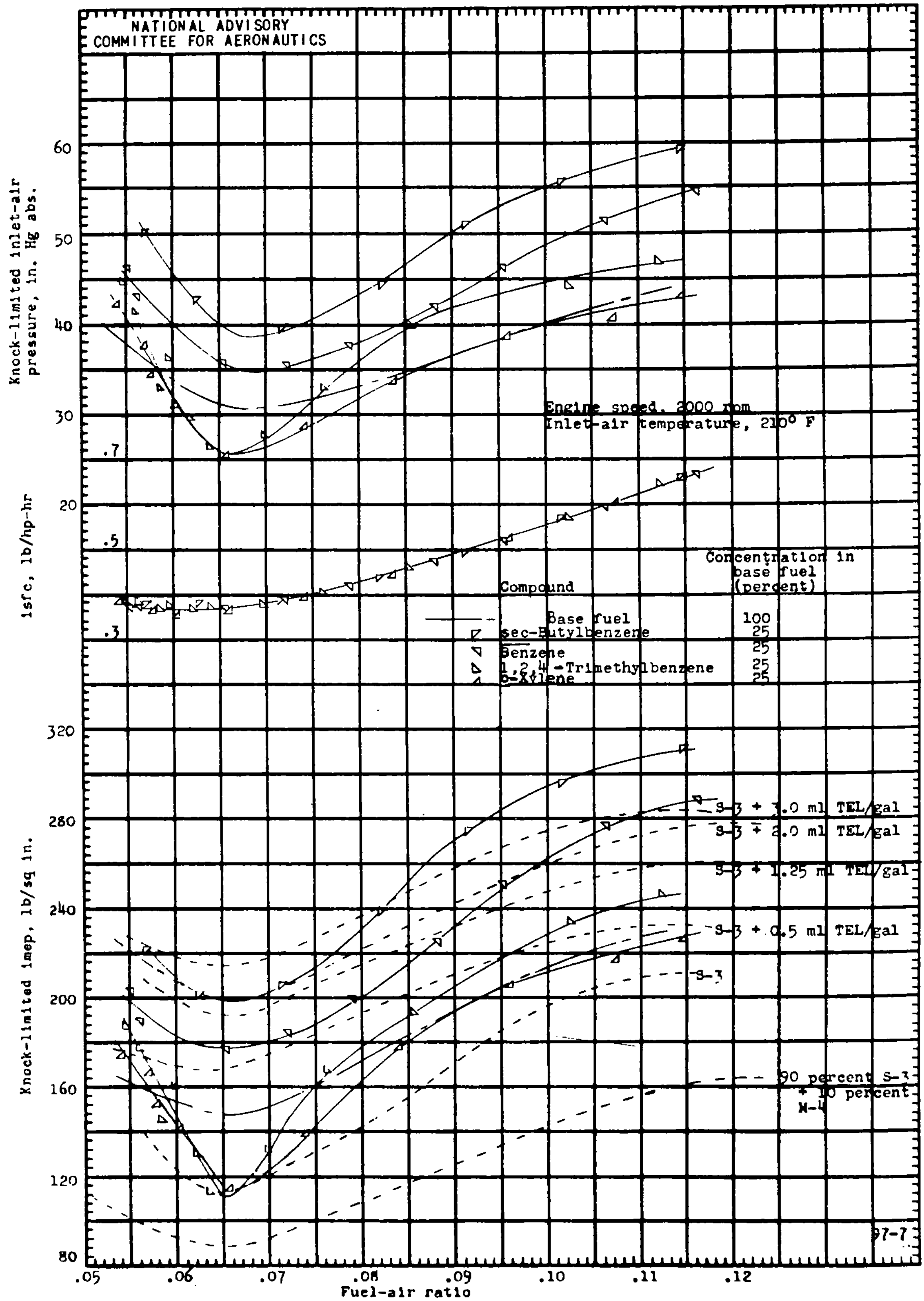


(a) 1,3,5-Trimethylbenzene, m-diethylbenzene, p-xylene, and 1-ethyl-4-methylbenzene.

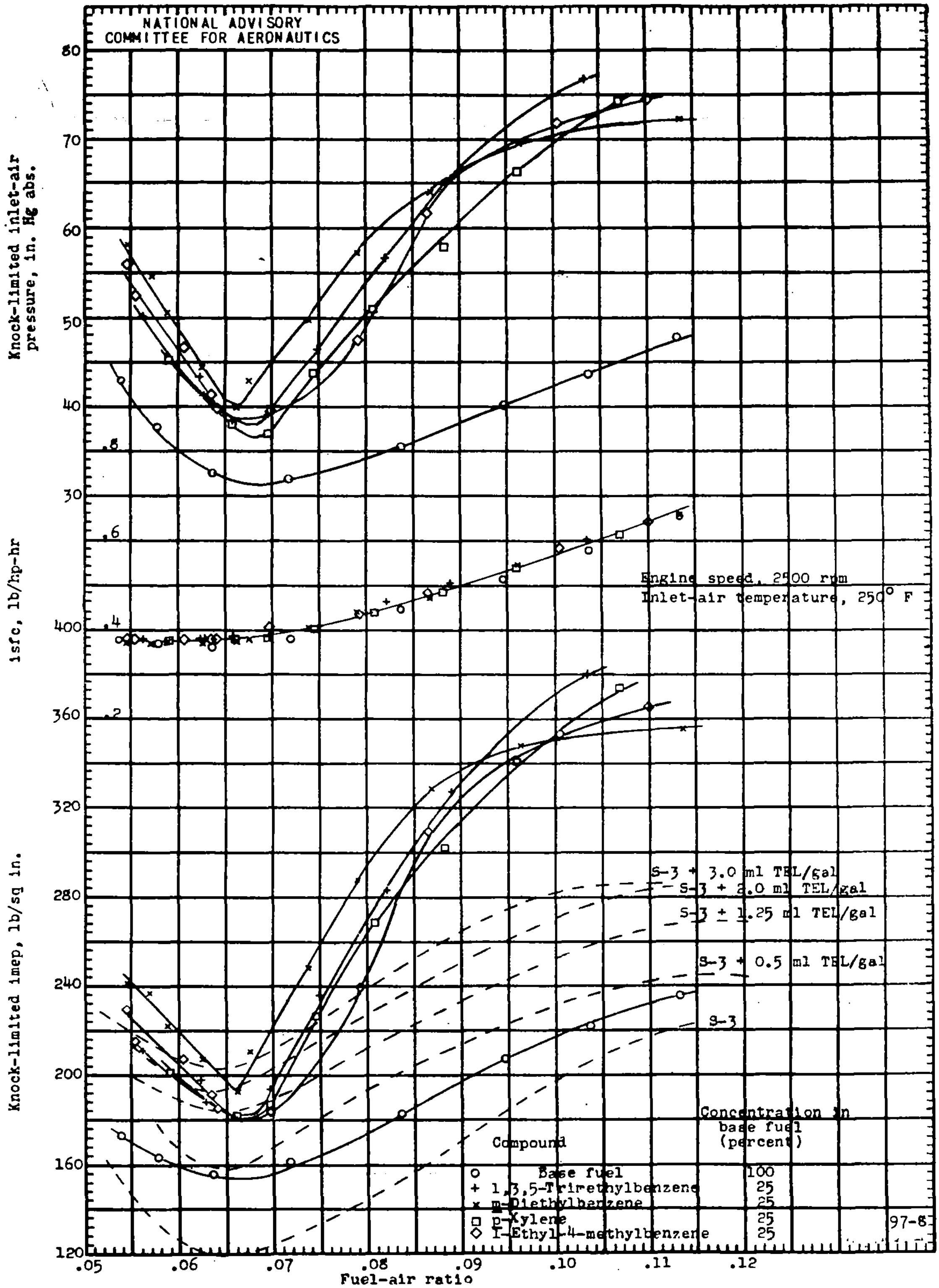
Figure 8. - Knock-limited engine performance of aromatic fuel blends at an engine speed of 2000 rpm and an inlet-air temperature of 210° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.



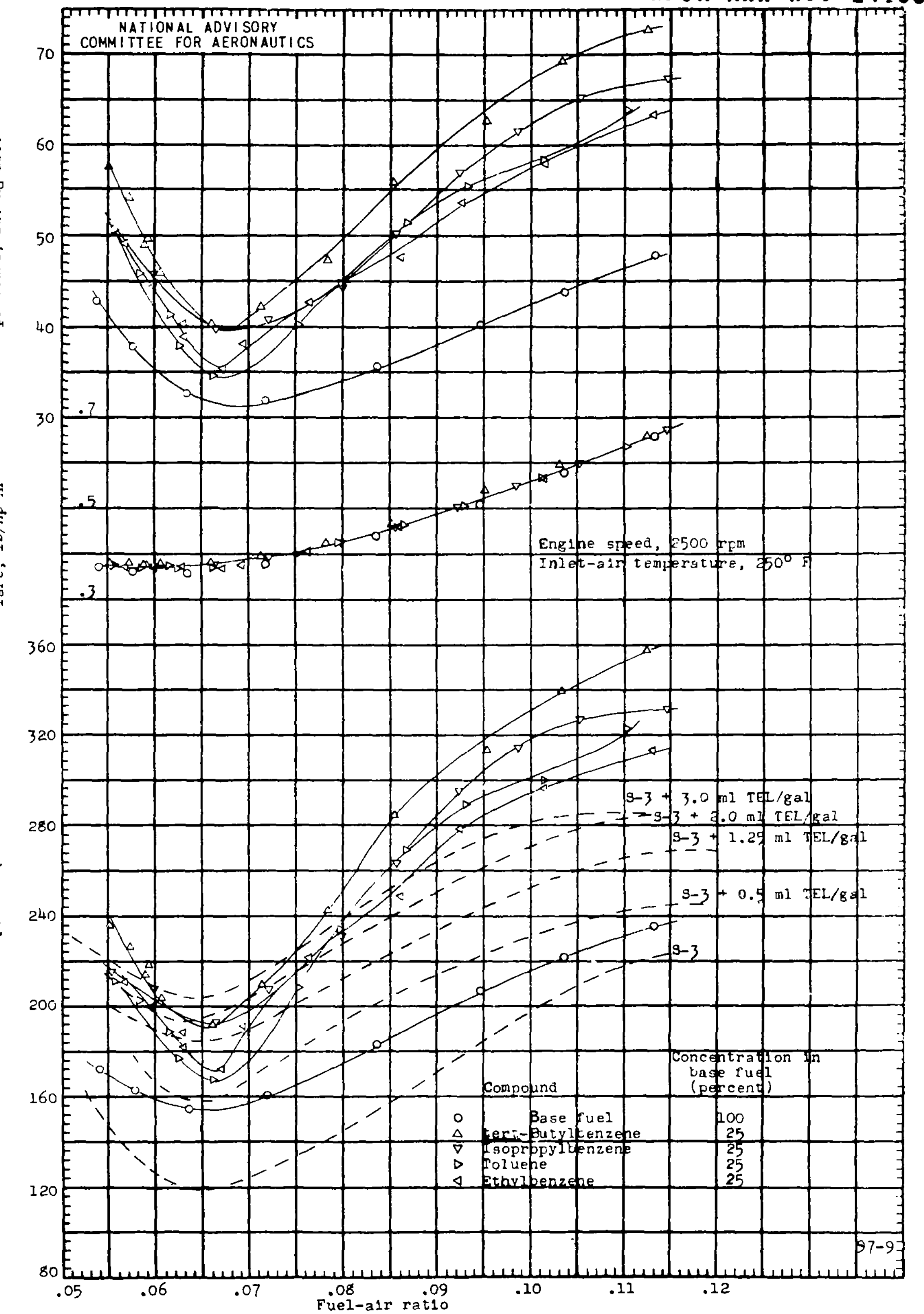
(b) tert-Butylbenzene, isopropylbenzene, toluene, and ethylbenzene.
Figure 8. - Continued.



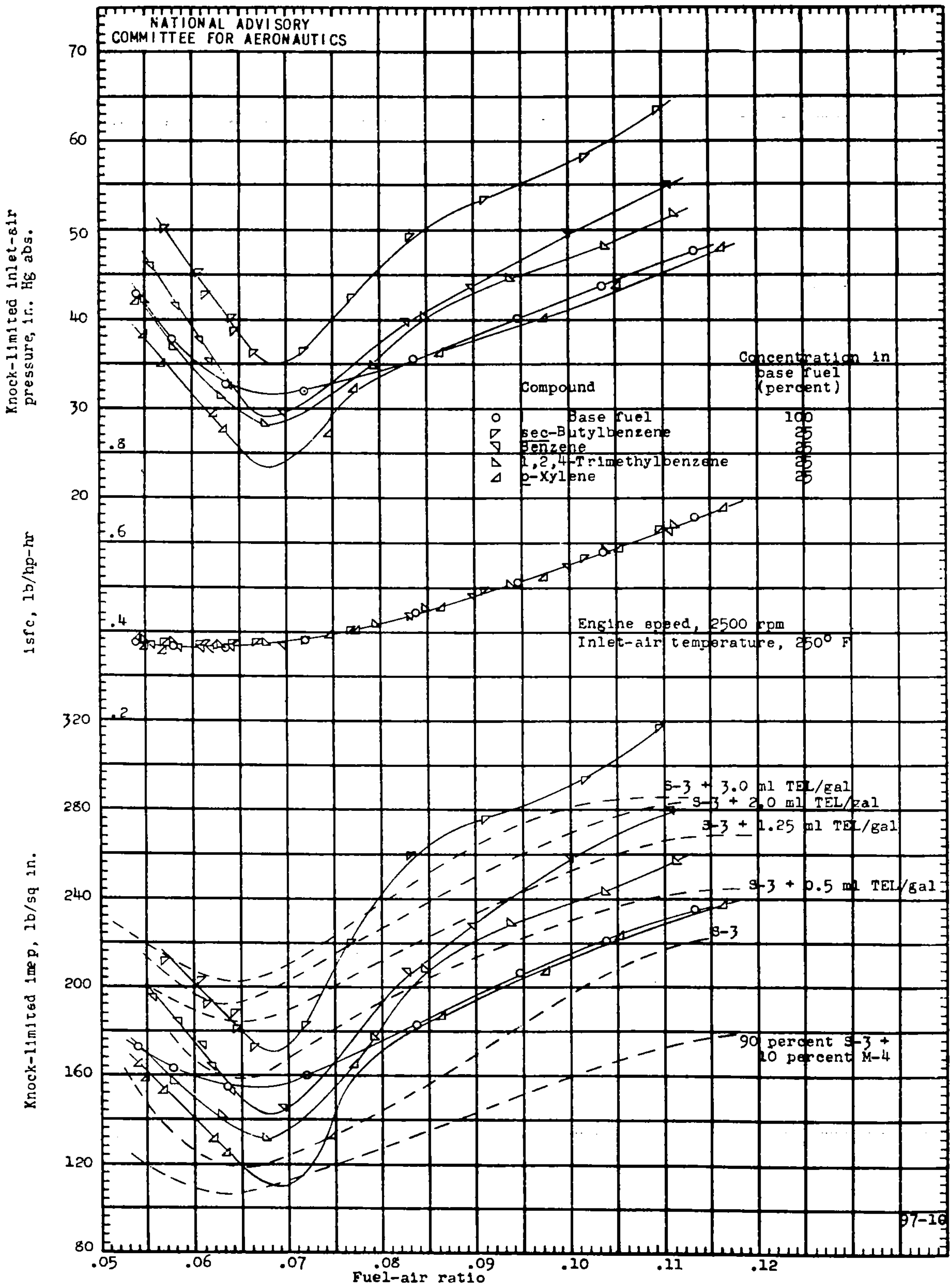
(c) sec-Butylbenzene, benzene, 1,2,4-trimethylbenzene, and o-xylene.
Figure 8. - Concluded.



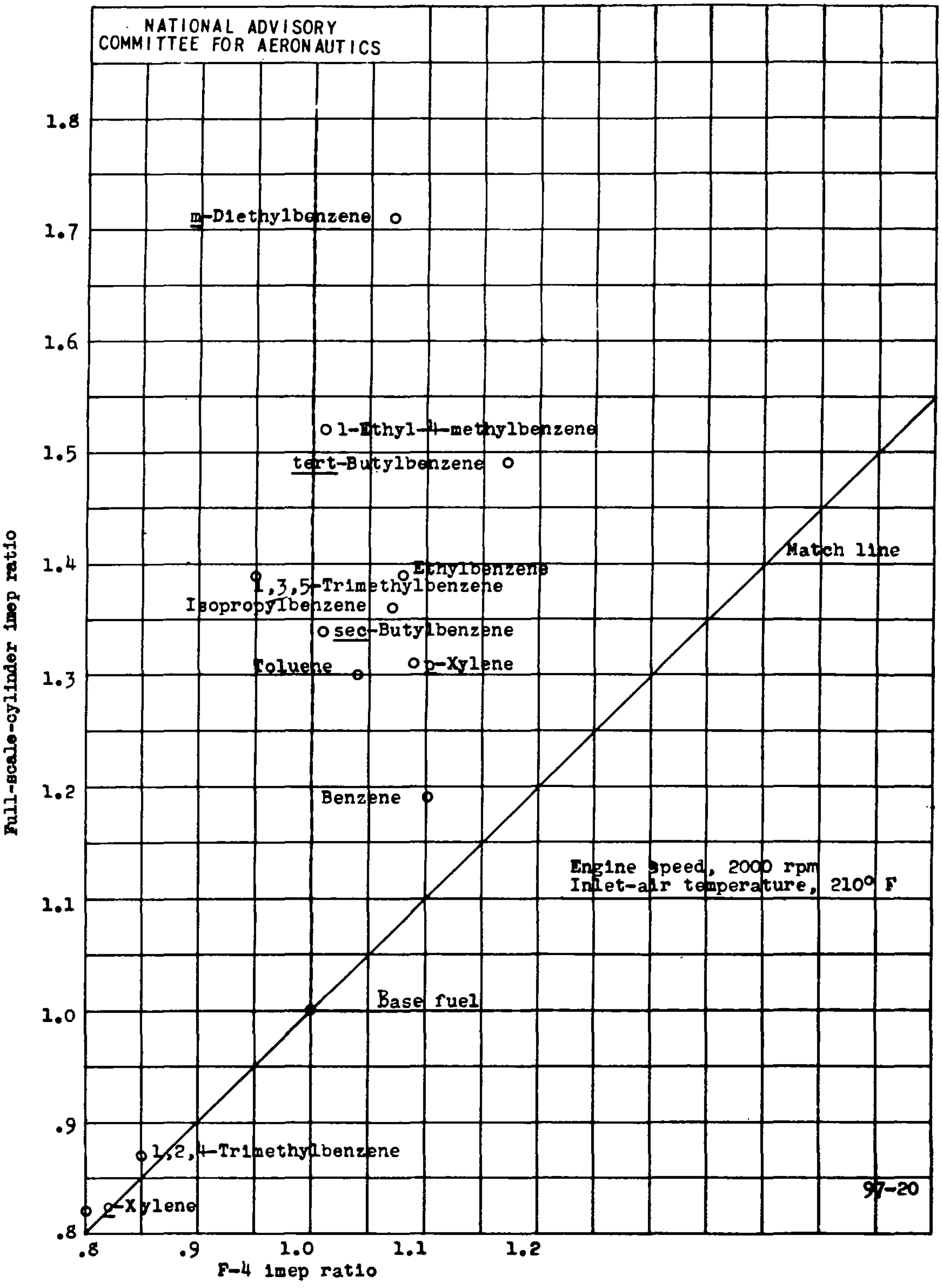
(a) 1,3,5-Trimethylbenzene, m-diethylbenzene, p-xylene, and 1-ethyl-4-methylbenzene.
Figure 9. - Knock-limited engine performance of aromatic fuel blends at an engine speed of 2500 rpm and an inlet-air temperature of 250° F. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.



(b) tert-Butylbenzene, isopropylbenzene, toluene, and ethylbenzene.
Figure 9. - Continued.

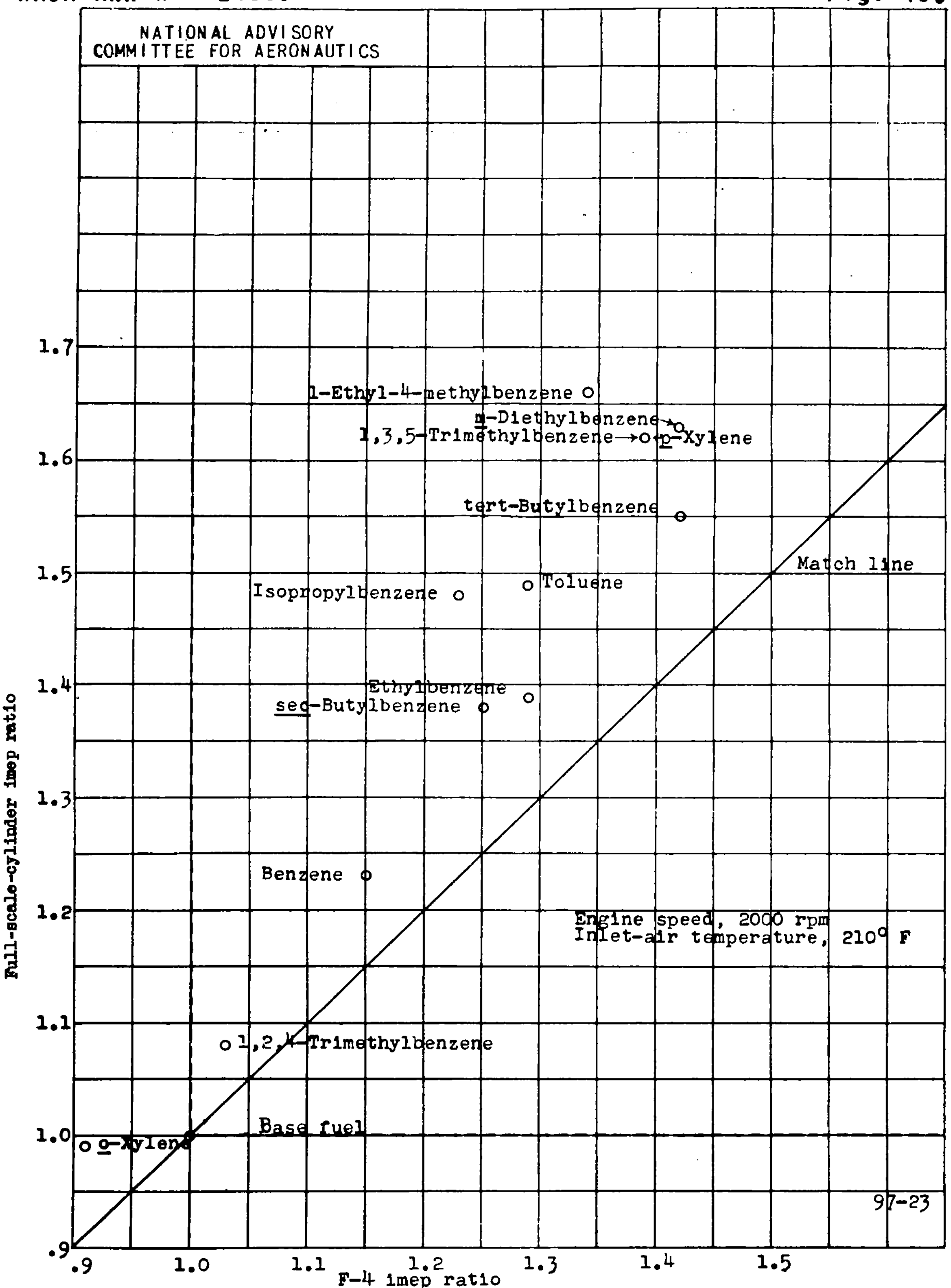


(c) sec-Butylbenzene, benzene, 1,2,4-trimethylbenzene, and o-xylene.
Figure 9. - Concluded.

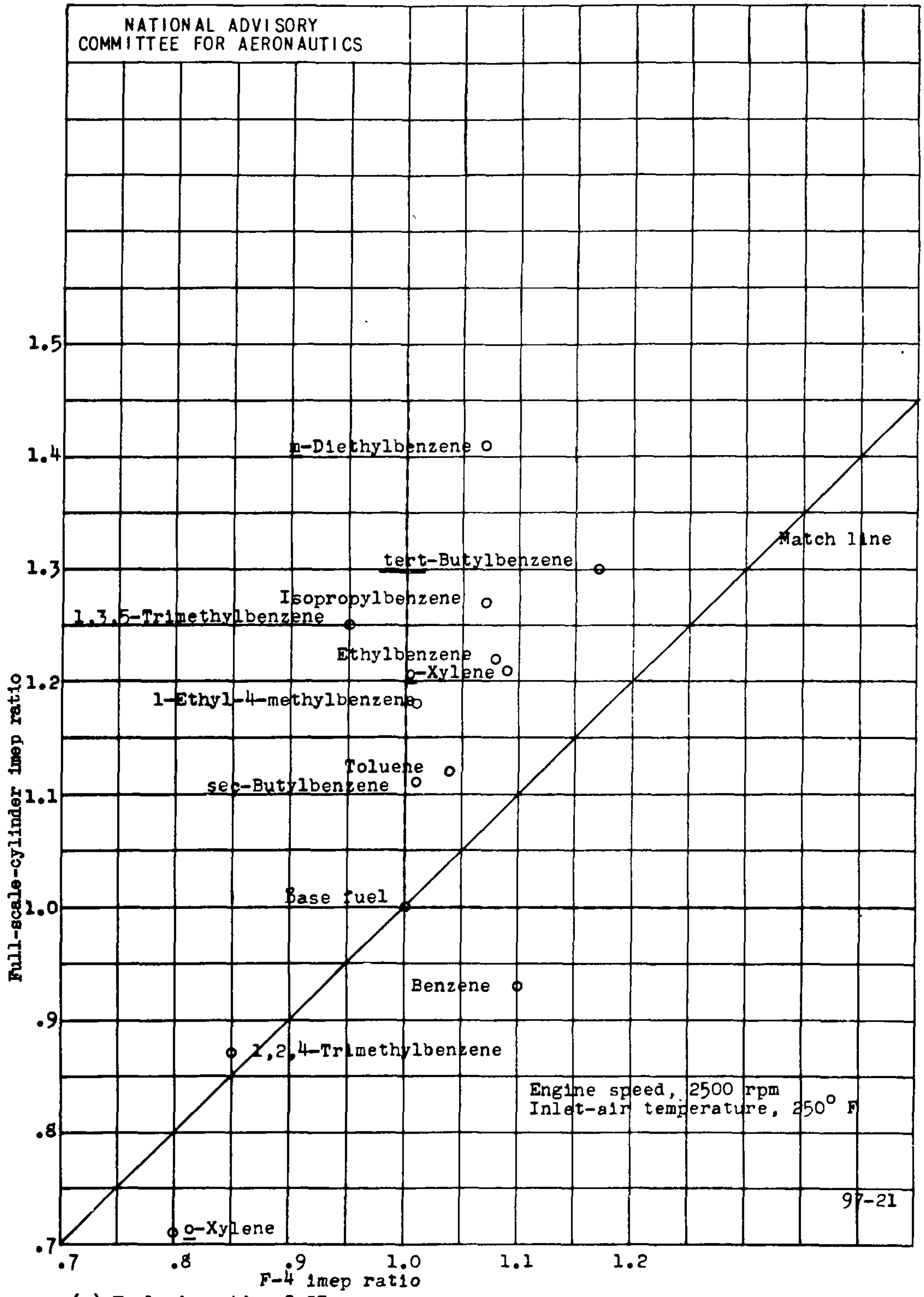


(a) Fuel-air ratio, 0.07.

Figure 10. - Comparison of fuel-blend performance at an engine speed of 2000 rpm with F-4 engine performance. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; inlet-air temperature, 210° F; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

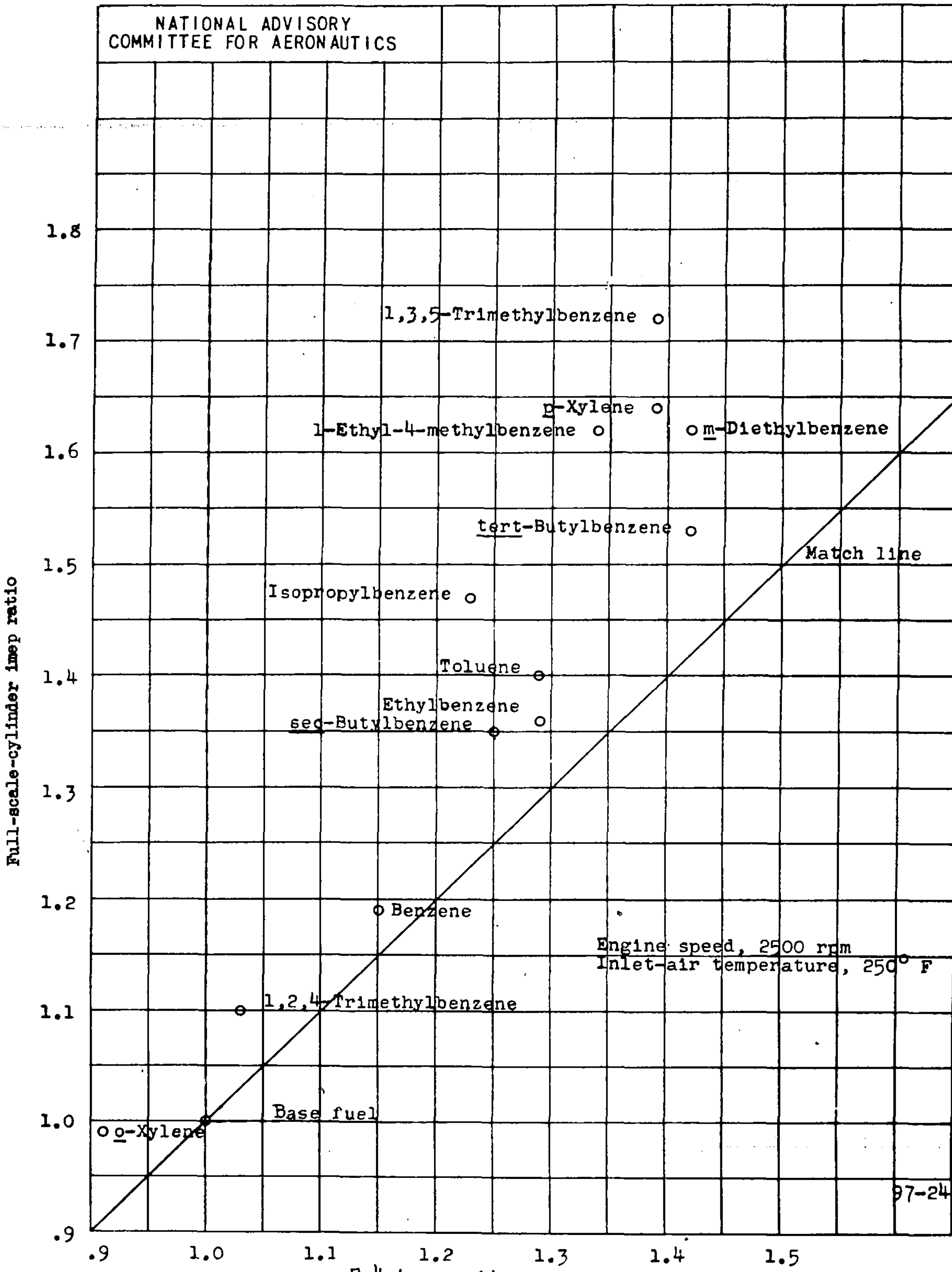


(b) Fuel-air ratio, 0.10.
Figure 10. - Concluded.



(a) Fuel-air ratio, 0.07.

Figure 11. - Comparison of fuel-blend performance at an engine speed of 2500 rpm with F-4 engine performance. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.



(b) Fuel-air ratio, 0.10.
Figure 11. - Concluded.

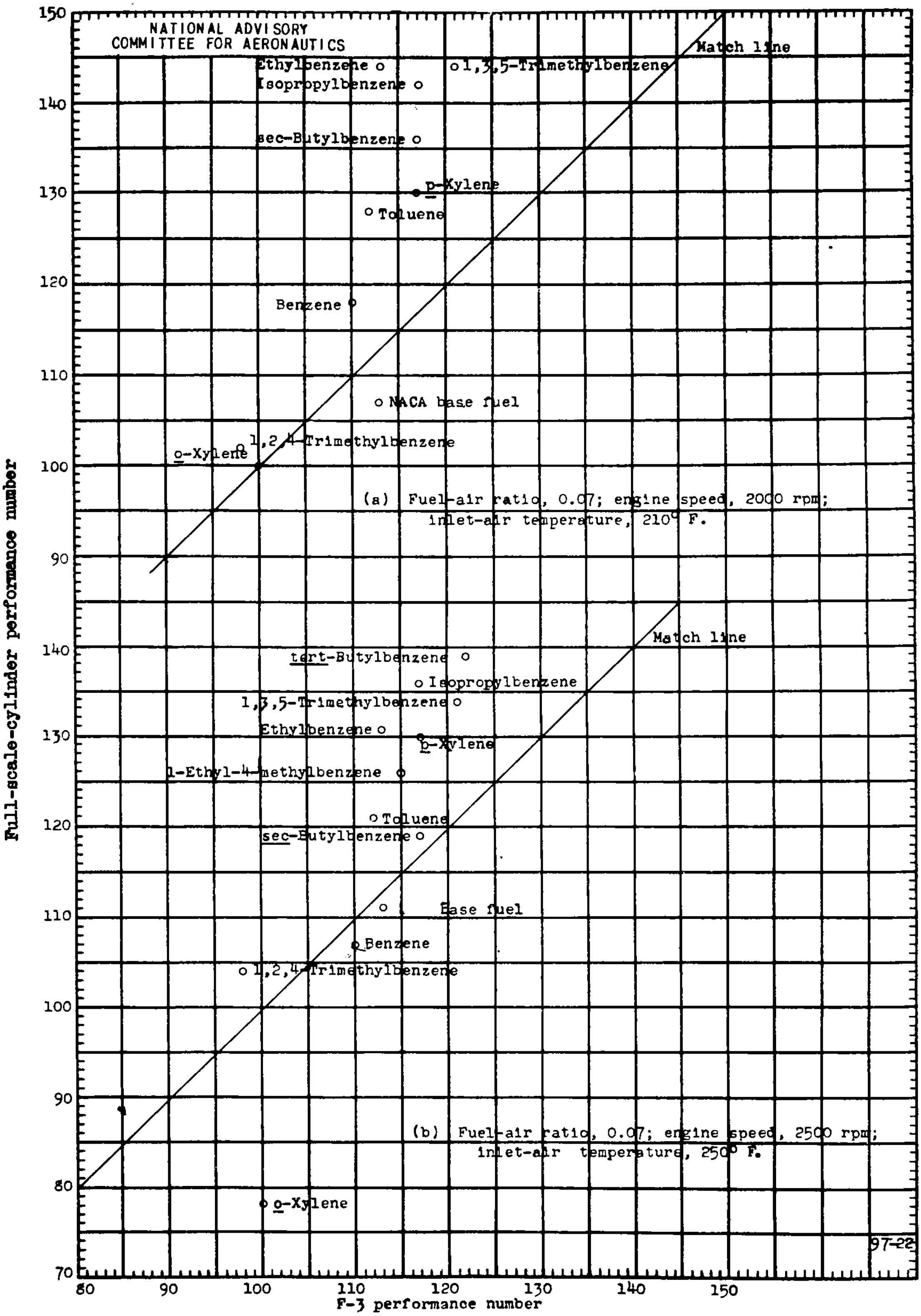


Figure 12. - Comparison of fuel-blend ratings with F-3 ratings. Full-scale aircraft-engine cylinder; compression ratio, 7.3; spark advance, 20° B.T.C.; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.